D180-17477-1

LIQUID – HYDROGEN – FUELED AIRCRAFT

NASA SYMPOSIUM

MAY 15 – 16, 1973

LANGLEY RESEARCH CENTER

THE BOEING COMPANY
SEATTLE, WASHINGTON

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INTRODUCTION

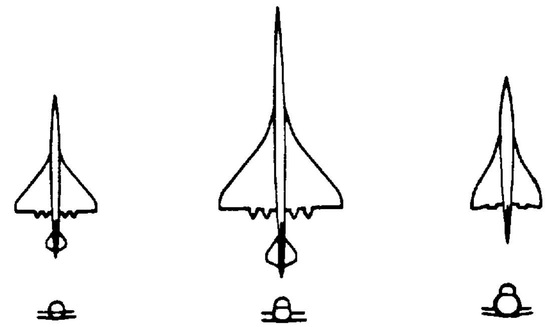
Boeing agrees that at some time in the future our fossil fuel economy will be superseded by a nuclear economy at which time hydrogen may become the most logical fuel for aircraft.

Boeing presents three aircraft configurations demonstrating that liquid-hydrogen fueled aircraft appear technically possible.

- A Supersonic Passenger Aircraft
- A Modified 747 Passenger Aircraft
- An Amphibian, Mobile Missile Carrier

Recommendations for research and development in the intervening time are made.

DESIGN TRENDS FOR LH_2 SUPERSONIC TRANSPORTS

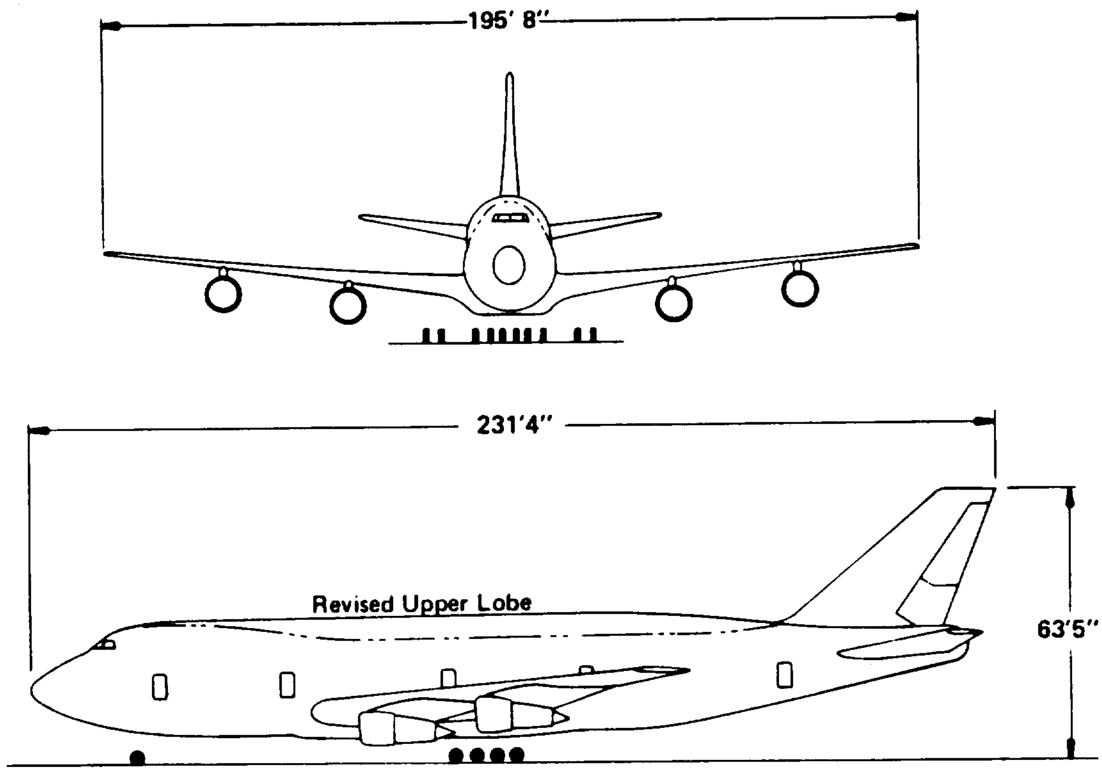


	2707-300	Scaled-Up 2707-300	LH_2 Design
Fuel	Kerosene	LH_2	LH_2
Gross Weight (Lbs)	750,000	1,200,000	650,000
No. of Passengers	250	480	250
Range (N Mi)	3,850	3,850	3,850
Fuel Burned (Lbs)	325,000	325,000	160,000
Wing Loading (Lb/Ft^2)	95	65	80

LH_2 could lead to a variety of new design approaches for supersonic transports.

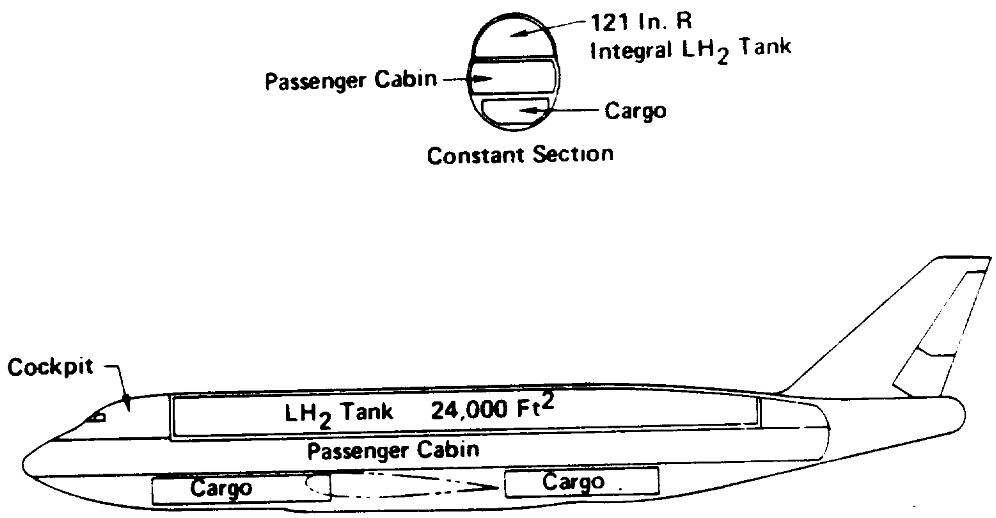
Scaling up of current configurations to provide the required volume results in larger payloads, lower wing loadings, and short field lengths. Tail-less designs become more competitive when field lengths are not critical. The tail-less approach could result in lower gross weights for the LH_2 case. Configuration optimization for a future LH_2 supersonic transport is a complex, new problem.

GENERAL ARRANGEMENT 747-LH_2



This picture shows a way to modify the 747 for LH_2 fuel. The upper lobe is expanded and carried over the full length of the fuselage. All fuel is carried in this upper lobe. Other component geometries are unchanged.

747-LH_2 INBOARD PROFILE



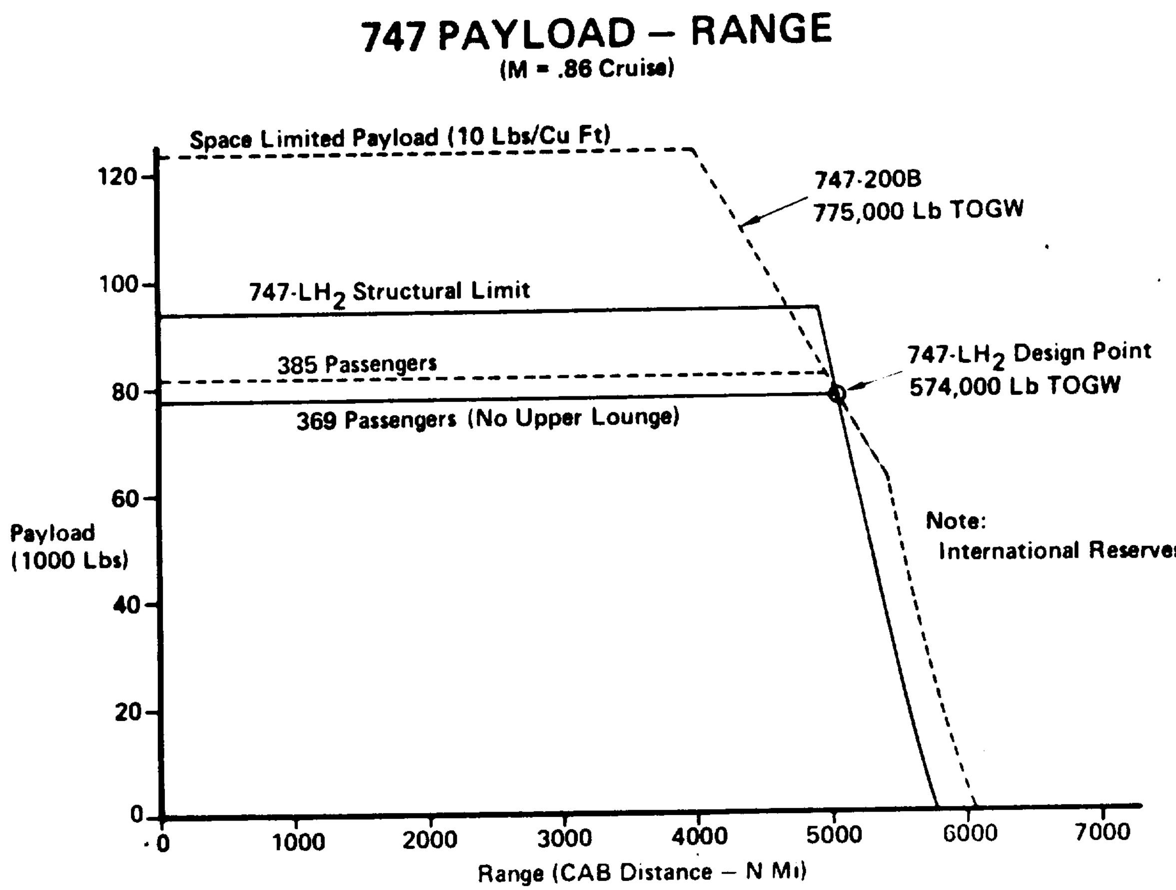
The inboard profile shows the fuel volume available in the modified upper lobe. Approximately 4000 cubic feet of LH_2 could be stored in the wing. The same amount of fuel volume can be obtained by a small increase in upper lobe diameter. This is preferable since it avoids the complexity of the wing fuel system.

The inboard profile shows the upper lobe as integral LH_2 fuel tank. Development of the technology for integral fuel containment is considered a critical design challenge.

COMPARISON OF 747 CHARACTERISTICS

	$747\text{-}LH_2$	747-200B
Fuel Type	Liquid H_2	JP-4
Max T.O. Weight	590,000 Lb	775,000 Lb
Passenger Capacity	369	385
Lounge Passengers	0	16
Mission Performance: (Full Passenger Payload)		
Range (M = .86)	5,100 N Mi	4,950 N Mi
T. O. Weight	574,000 Lb	775,000 Lb
Fuel Burned	90,500 Lb	268,000 Lb
T.O. Field Length	5,150 Ft	10,200 Ft
Initial Cruise Altitude	36,000 Ft	31,000 Ft

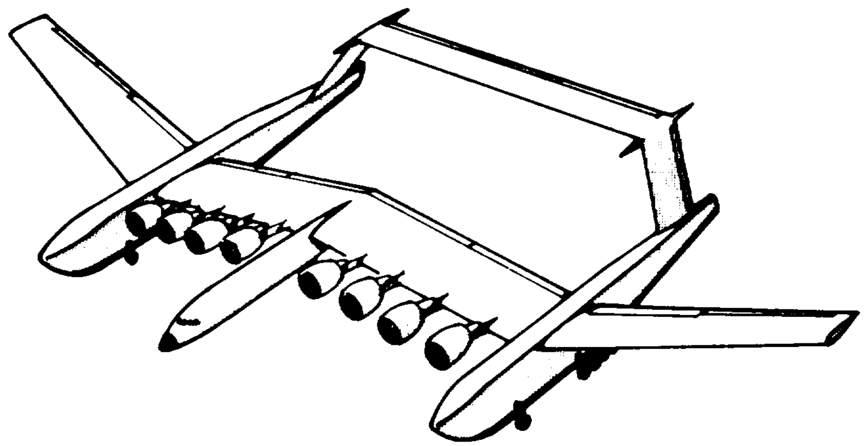
The above comparison shows that LH_2 enables the 747 to carry essentially the same passenger load over an equivalent range at a 24 percent lower takeoff weight. Reduced runway length and/or reduced noise and higher initial cruise altitude are direct benefits of the lower gross weight. Trade-offs between these parameters will make it possible to optimize the system for the prevailing conditions at the time LH_2 is introduced as aircraft fuel.



This payload-range diagram shows two interesting points:

- Whereas in today's JP-4 fueled aircraft payload can be traded for fuel, thus extending the range of the aircraft, the LH_2 aircraft is basically fuel volume limited.
- Centerline loading of all LH_2 fuel lowers the maximum payload capability because of wing strength limitations. The JP-4 fueled aircraft benefits from the wing bending relief provided by the wing fuel.

AMPHIBIAN MOBILE MISSILE SYSTEM



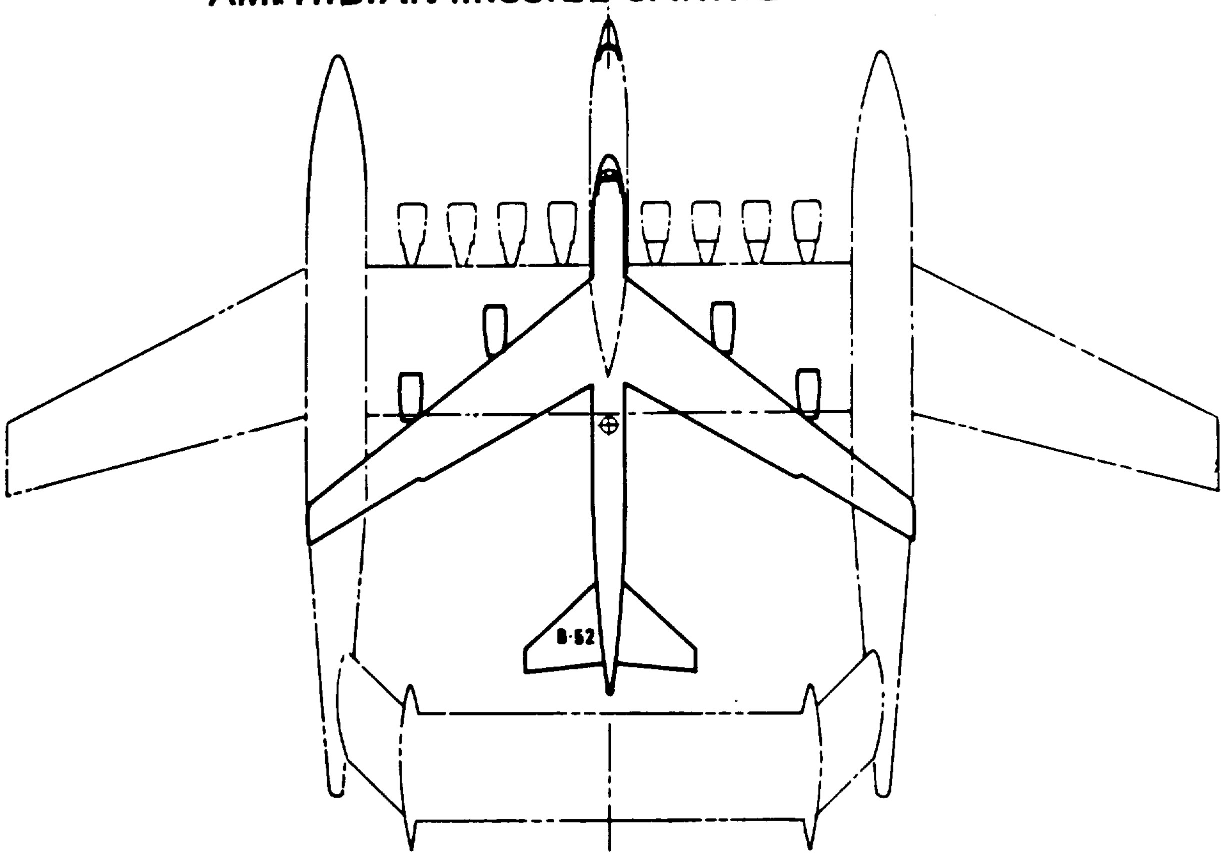
Takeoff Weight = 2.0 Million Lbs
Payload = 324,000 Lbs
Fuel = LH_2 or JP

This aircraft mobile missile system is intended to provide first strike survival and very long rundown time. First strike survival is provided by dispersal capability and mobility. The long rundown time is achieved by the capability to sit on the ocean or other bodies of water until called into action.

Size and design of the aircraft are such as to permit takeoff and landing at sea state 3. Ride-out is possible in much higher sea states.

Size and configuration of the amphibian aircraft are suitable for JP or LH_2 fuels without change in geometry. Integral containment of the LH_2 in the two hulls is required to provide the desired amount of fuel.

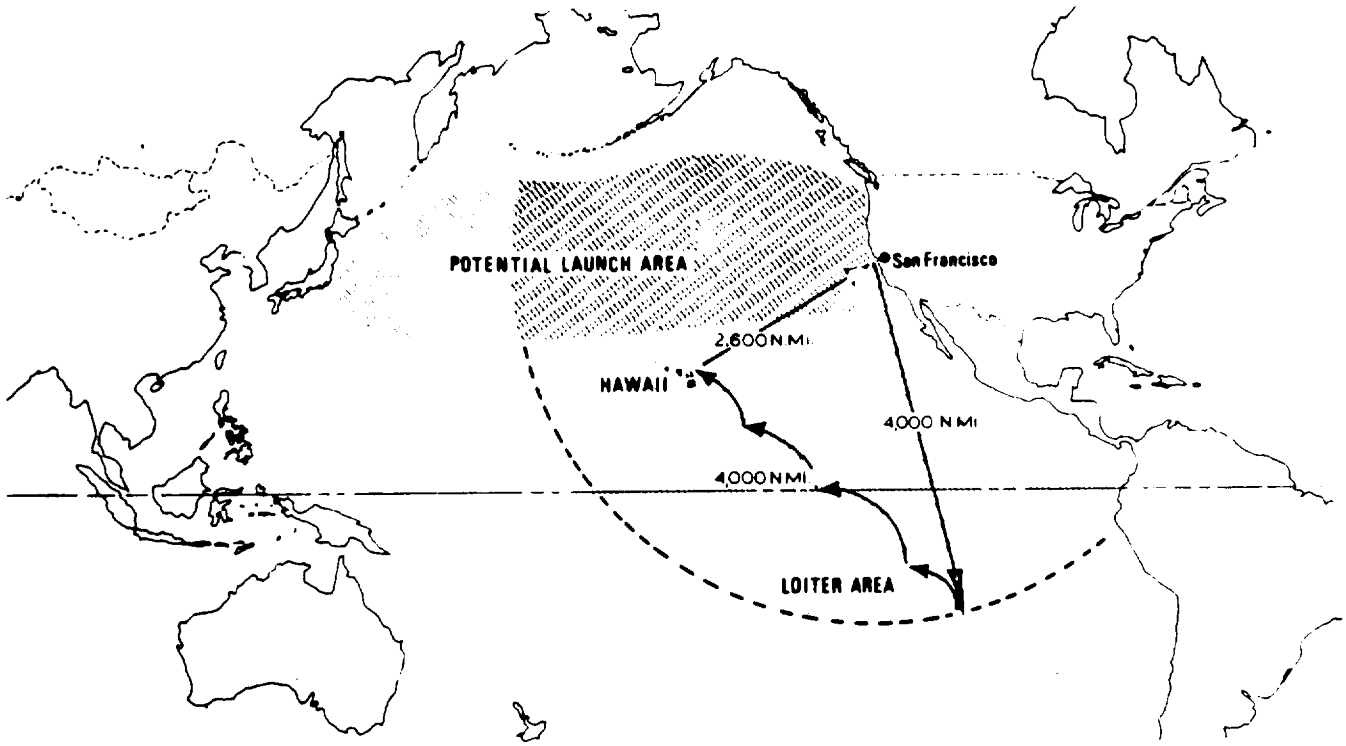
SIZE COMPARISON OF AMPHIBIAN MISSILE CARRIER AND B-52



This comparison shows the size of aircraft required for water operation at 1.8 million pounds hull-borne weight.

The large twin hulls primarily required for flotation, have the integral space to carry 800,000 pounds of LH_2, giving the aircraft an unrefueled, continuous flight range of over 17,000 nautical miles.

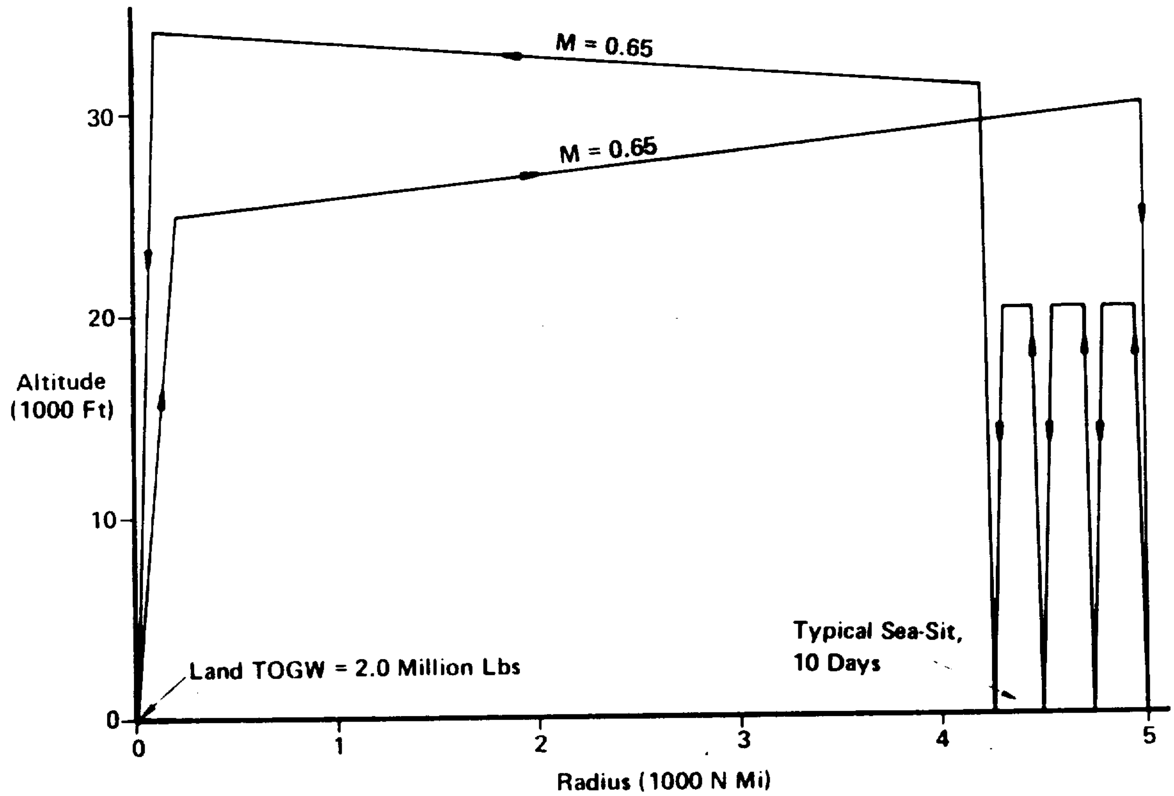
MISSION CONCEPT – AMPHIBIAN MISSILE CARRIER



The mission concept envisions take-off from U.S. bases, dispersal in equatorial latitudes, changes of "ocean-sitting" positions during the holding portion of the mission, and return to base on a dogleg to Hawaiian latitudes.

Coverage of Northern Hemisphere target areas is possible from about latitude 30° north and launch points are available in a vast area remote from simple surveillance.

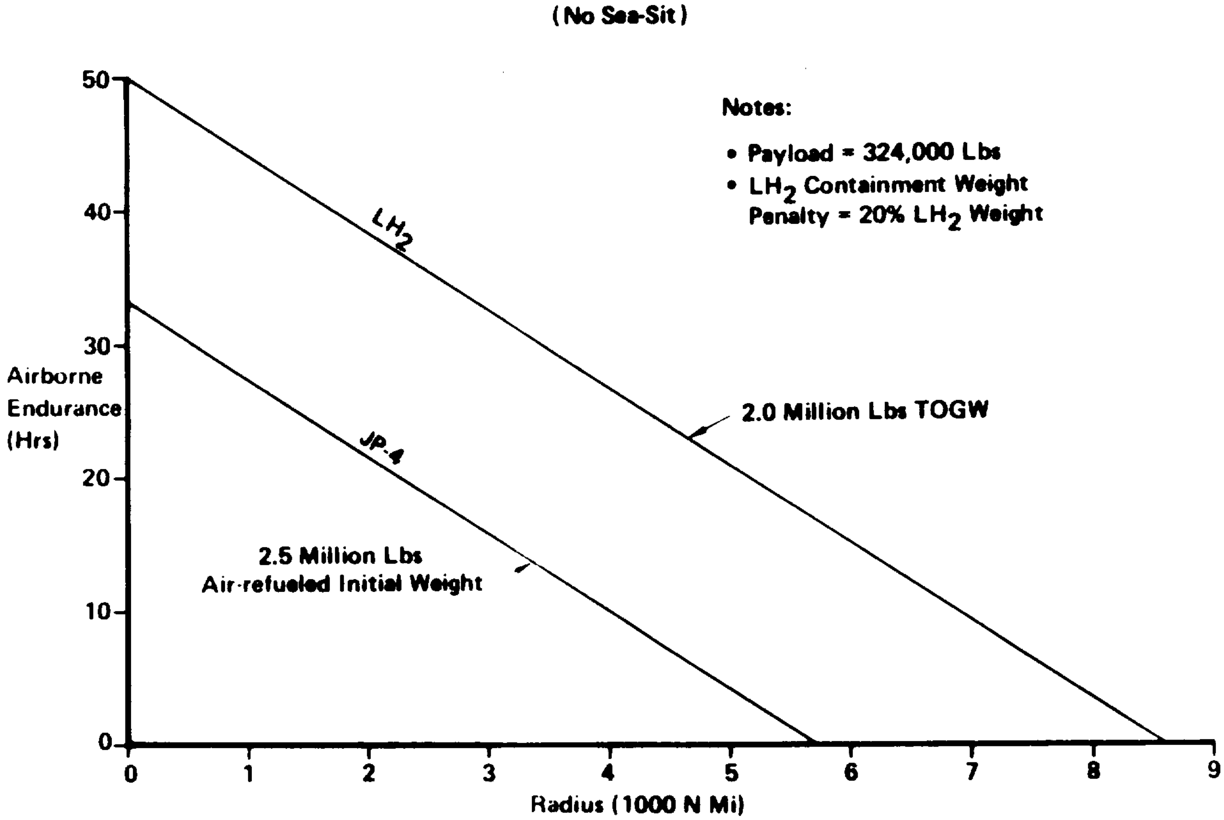
TYPICAL FLIGHT PROFILE, LH_2 FUEL



This Vu-foil depicts a typical peace time mission of 10 days duration. The range of the aircraft makes it possible to reach the launch point and to return to base at any time.

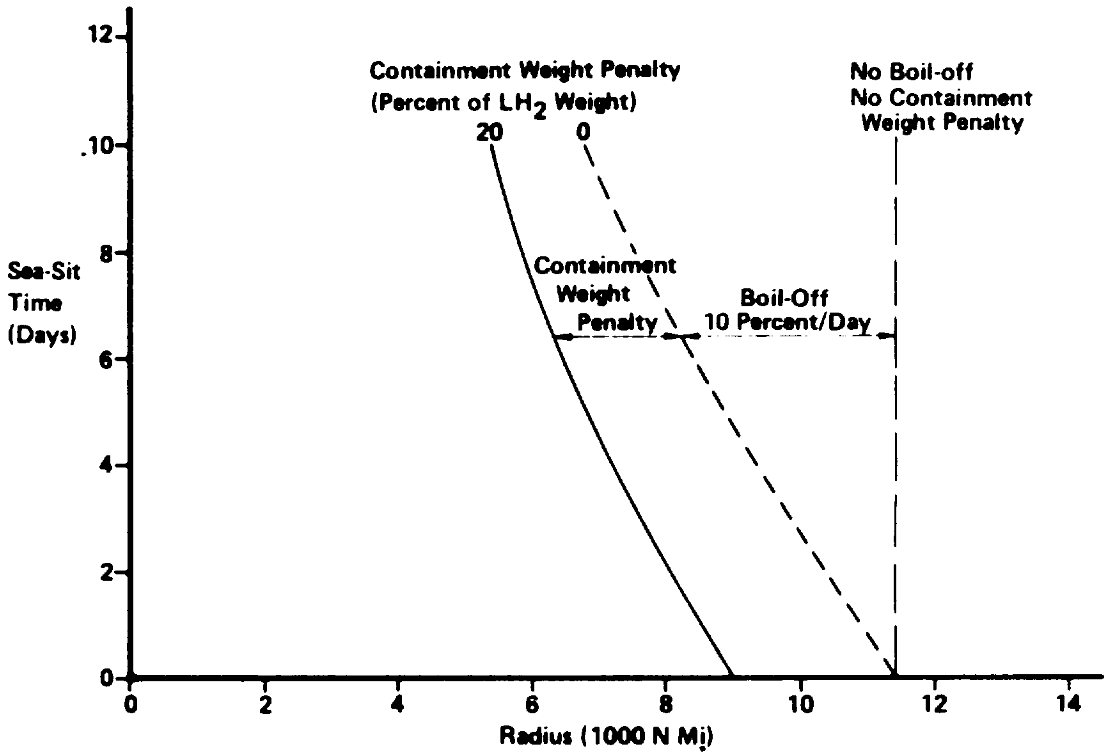
The change of location is shown to be flown at 20,000 feet, but it could take place at lower or higher altitude to take maximum advantage of cloud cover. The low cruise speed of M = .65 is fundamental to low structural weight and long endurance.

AIRBORNE PERFORMANCE COMPARISON



This graph shows the performance (endurance/range) improvement of the LH_2-fueled aircraft over the conventional, JP-4 burning aircraft. The JP-4 aircraft is air refueled to a 2.5 million overweight condition. The LH_2 aircraft is unrefueled and has been assessed 160,000 pound weight penalty for the containment of the cryogenic fuel, and still shows a 50 percent performance improvement over the conventional airplane.

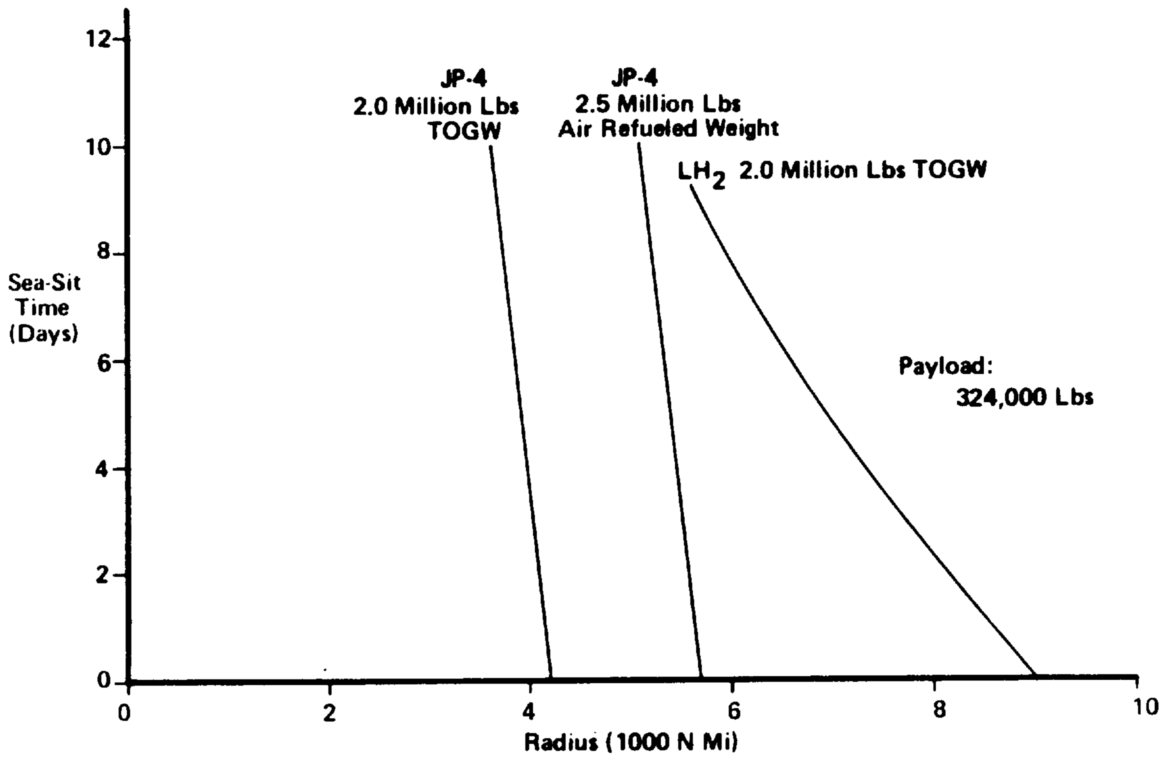
EFFECT OF BOIL-OFF AND CONTAINMENT ON AIR-SEA MISSION PERFORMANCE



This graph illustrates the penalties incurred for fuel containment and boil-off. Research and development of fuel containment has a significant potential payoff. A reduction of boil-off immediately increases the practical mission duration, reduces the number of aircraft needed and lowers total life cycle cost.

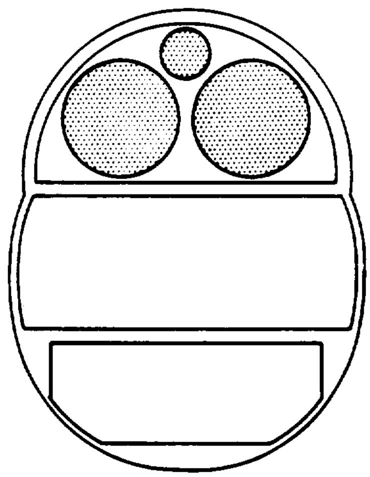
Operation of an APU during the entire mission appears to be a necessity (life support systems, command and control, passive sensors). Trade-offs between system weight and complexity for fuel refrigeration and fuel loss by simple boil-off appear worthy of investigation.

LH_2 – JP-4 COMPARISON

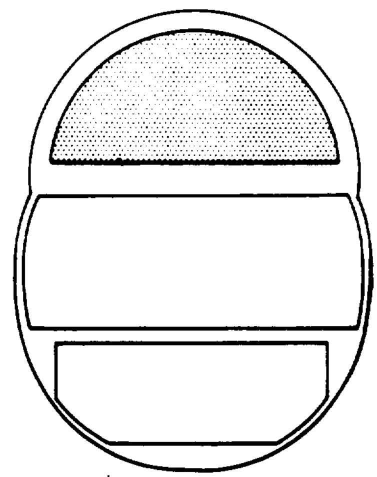


This picture illustrates another aspect of the LH_2 fueled aircraft: LH_2 boil-off results in a cross-over between the JP-4 and the LH_2 aircraft. Range and airborne endurance of the LH_2 fueled aircraft decay more rapidly than of the JP-4 aircraft, limiting the practical run-down time of the LH_2 systems to about half the endurance of the JP-4 system. The operational significance of this effect needs to be assessed.

INTEGRAL FUEL CONTAINMENT



78 Percent
Volume Utilization



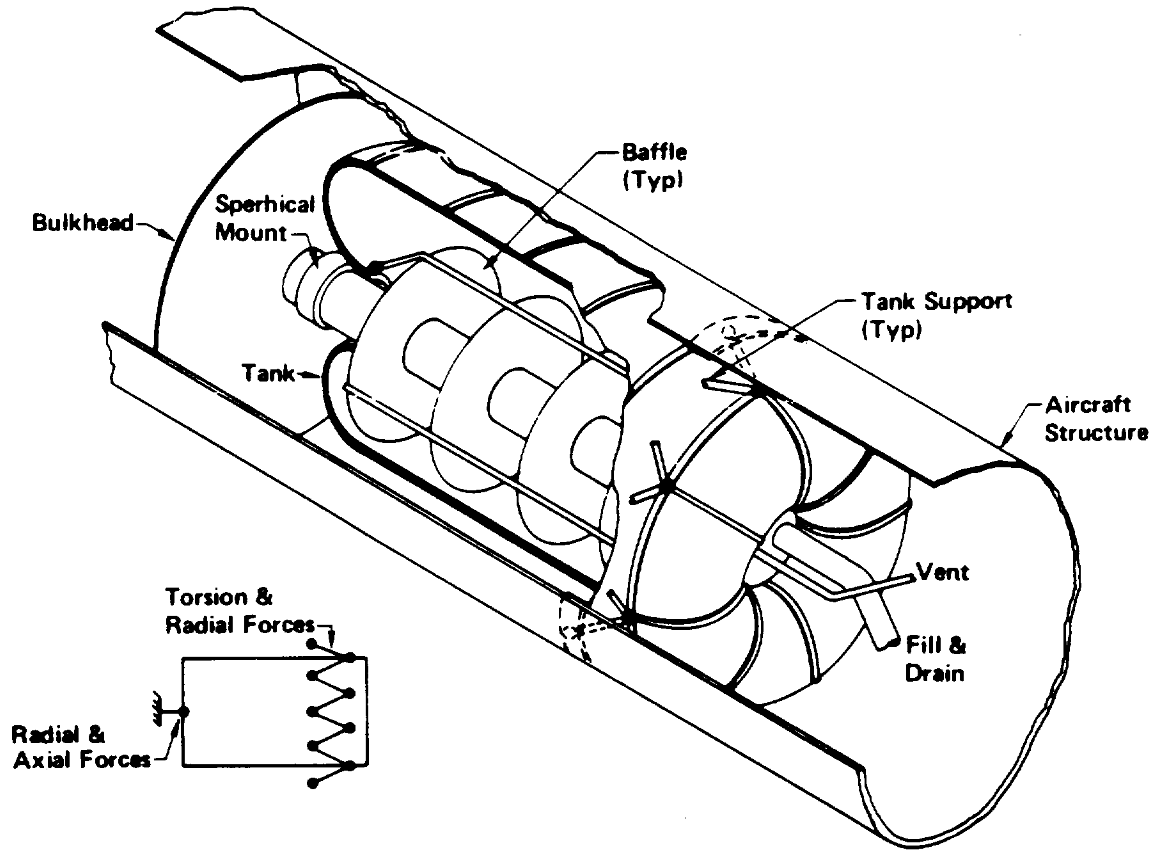
100 Percent
Volume Utilization

The sketches shown here illustrate what to us appears to be the most critical design problem of LH_2 aircraft: integral fuel containment.

Todays technology contains the LH_2 in insulated, cylindrical pressure vessels. Considering the aerodynamic geometry requirements of aircraft this results in poor space utilization and, because of the unfavorable surface to volume ratios, high weight penalties for containment and insulation.

Solving the problems of integral LH_2 containment in the non-cylindrical, configuration dictated structures could result in more efficient aircraft.

CRYOGENIC FUEL CONTAINMENT



This Vu-foil illustrates ways to deal with the problems of cryogenic fuels, e.g., LH_2, in a conventional fuel tank.

The fuel tank is suspended in the aircraft structure analogous to a typical engine installation. The front end of the tank suspension absorbes radial and axial loads, but no bending moments. The aft suspension takes radial loads only and the links provide for unrestrained axial and radial contraction and expansion of the tank.

The central front mount and the aft links minimize heat conductive paths and thus help to reduce boil-off. Similarly, the slosh baffles attached to the central member provide no path for heat conduction to the outside structure.

Venting of the space between fuel tank and outside aircraft structure prevents the build-up of explosive air-hydrogen mixtures. Inerting of this space is possible.

The integral tank system must resolve the problems of thermal expansion, insulation and fire prevention in a similarly reliable fashion.

R&D REQUIREMENTS IN SUPPORT OF LH_2-AIRCRAFT

Materials

- **Tanks and Lines**
- **Insulation**
- **Expulsion Bladders**
- **Mechanical Components, Interiors, Tools (Non-Sparking)**

Design

- **Thermal Expansion**
- **Fatigue**
- **Minimum Heat Loss, No Ice Build-Up**
- **Long Life Pumps**

Safety

- **Inspection and Maintenance**
- **Procedures**
- **Penetration and Lightning Strike**
- **Fail Safe Design**

The primary goal of the R&D efforts should be to make the LH_2-aircraft as safe as today's JP-4 fueled aircraft. The wide flammability range of air-hydrogen mixtures and the low ignition energy required to initiate combustion make safe operation of LH_2-aircraft a primary concern.

Design safety must encompass containment and inerting to avoid formation of explosive mixtures as well as elimination of potential ignition sources. The latter includes selection and packaging of all electrical and electronic components, protection against lightning strikes, selection of non-sparking materials and materials that do not build up static electricity. Overheating of mechanical equipment, such as pumps, must be guarded against.

Safety will be the major problem area of LH_2-aircraft.

SUMMARY OF BOEING'S POSITION AND RECOMMENDATIONS

- LH_2 Is a Potential, Future Aircraft Fuel
- LH_2 Fueled Aircraft Will Generally Be Large
- Aircraft May Be Last Energy Consumer to Convert From Fossil to LH_2 Fuel
- Conservation of Fossil Fuel Is Top Priority
- Recommend NASA R&D Emphasis on Maximizing Passenger-Mile, Ton-Mile Per Pound of JP
- Integral Fuel Containment Is a Critical Design Problem for LH_2 Aircraft
- NASA R&D on Fuel Containment Beneficial to Non-Aircraft Use

Nuclear power will eventually be the principal energy source. Use of liquid hydrogen as aircraft fuel will be a distinct possibility at that time. The problems arising from LH_2 fueled aircraft appear soluble and LH_2 may even offer advantages for certain applications. The timing of this development appears to be of essence in deciding where to place R&D emphasis.

Fossil fuels will provide the largest share of our energy needs for the next 40 years. Conservation of fossil fuels will be given a high national priority. In this environment it will be essential for the aerospace industry to promote energy conservation and to gain public visibility for these efforts. Priority should be given to R&D efforts to maximize passenger-miles and ton-miles per pound of JP fuel consumed. Development of aircraft, engines, and operational concepts that permit aviation growth while conserving fuel will aid in maintaining a healthy aerospace industry.

Aircraft solutions for integral LH_2 containment might result in system efficiency benefits. R&D expenditures for integral containment solutions are believed timely for future LH_2 airplanes.

Ground based hydrogen fuel systems are likely to precede LH_2 airplanes. Aerospace industry background in hydrogen and cryogenic systems could prove valuable in the development of the ground based systems.